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Magnetic Field Mapping for Complex Geometry Defect - 3D Transient Problem

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Abstract

A 3D visualisation of transient magnetic field mapping via finite element simulation for the characterisation of complex geometry defect is presented in this paper. In this work, we analyse the Pulsed Eddy Current (PEC) testing application on detection and characterisation of complex geometry defect, i.e. angular slots, through the mapping of magnetic field distribution subject to the interaction between eddy current and defects in conductive samples. The investigation is implemented via time-stepping 3D Finite Element Analysis (FEA). Finite Element (FE) simulations conducted in transient mode were explored for the characterisation of angular slots. The results indicate the potential of complex geometry defect characterisation based on the visualisation and mapping of the magnetic field distribution. It is expected that the investigation will help in sensor (array) design and inverse models for complex geometry characterisation.

Keywords: Transient magnetic field mapping, Pulsed eddy current, Complex geometry defect, Finite element analysis

1. Introduction

Eddy current testing (ECT) is one of the Non Destructive Testing (NDT) methods which work on electromagnetic principles and is widely used on electrically conductive samples. It allows the inspection of surface breaking as well as subsurface discontinuities, due to the eddy current distribution in the samples. The excitation frequencies directly affect the probability of detection for subsurface discontinuities due to the skin effect [1]. In ECT, the excitation coil driven by an alternating current generates a magnetic field which induces eddy currents in conductive materials. In contrast to most eddy current (EC) techniques, Pulsed Eddy Current (PEC) uses transient waveforms for their coil excitation. The wideband pulse consists of a series of frequency components leading to richness of information gathered about the defect [2-4].

For the purpose of unveiling the electromagnetic phenomena underlying the PEC systems, theoretical study has been conducted for several years and began with analytical modelling for time-harmonic on layered structures, following which numerical simulations using finite element analysis (FEA) [5-7]. After the time-stepping solver was introduced in FEA, 2D and 3D simulations are prevalent in solving PEC problems. Li et al provided analytical and FEA models to predict the eddy current response and variation of magnetic field to flawed specimens such as conductors with corrosions or inclusions when the inspection probe moves over the samples [6]. To the knowledge of authors', the analytical modelling for EC and PEC are mostly focused on specimens with simple geometries such as stratified conductors or samples with slots [8, 9]. One significant advantage of FEA over analytical modelling lies in the fact that it is intricate for analytical approaches to predict magnetic field interaction with complex geometrical defects which precludes closed-form analytical approaches [10-12].

In this paper, to analyse the PEC testing application towards complex geometrical defect, i.e. angular slots, a time-stepping method using Finite Element Analysis (FEA) was applied to a 3D transient problem. We have taken the forward approach of characterising the complex geometry defect based on the visualisation of the resultant magnetic field mapping from the interaction between the eddy current and the defects in the sample. Particularly, the potential of 3D visualisation of magnetic field distribution for complex geometry defects characterisation is explored.

This paper is organised as follows: Section 2 presents the model setup for PEC simulations; Section 3 introduced the 3D visualisation of magnetic field; Section 4 presents the angular slots characterisation from the magnetic field mapping and the discussions of the results; Section 5 gives the conclusion and the focus of future work from the outcome of this work.

2. Simulation Model and Setup

In Electromagnetic Non-Destructive Evaluation (ENDE) field, it is essential to build the relationship of magnetic field distributions and different defects including 3D shape, size and location, which facilitates not only forward problems but also the inverse process involving sensor array configuration, pattern recognition, defect quantification and reconstruction of 3D defects. Consequently, a series of numerical modelling regarding to transient magnetic field distribution under complex geometry defect are conducted.

In the simulation, the coil used has the dimensions of 14 mm inner diameter, 16 mm outer diameter, 1 mm height and 1000 turns of wires, and is driven with a rectangular waveform to generate a varying magnetic field. Aluminium samples with long angular slot of depth 5 mm and width 1 mm with an angle of 0^0, 10^0, 20^0, 30^0 and 40^0 were modelled and the resulting magnetic field along the coil axis, which is vertical to the sample surface, was visualised for the 3D transient magnetic field mapping of the angular slots.

In the time-stepping FEA, the transient magnetic field visualisation was made when the coil is positioned above the slot opening; where the excitation pulse width is 1 ms and pulse repetition frequency is 200 Hz. All simulations were performed using MAGNET by Infolytica Ltd. Figure 1 shows the layout of the coil and the sample having complex geometry defect modelled as a 3D problem.

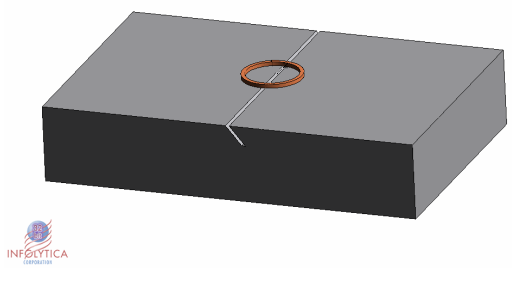


Figure 1. 3D model of the coil and sample with an angular slot

3. 3D Visualisation

Finite element (FE) simulation for the 3D visualisation of magnetic field was conducted in transient mode. The simulations were conducted to visualise the magnetic field distribution change under complex geometry defect. Figure 2 shows the simulations of angular slots with eddy current distribution in samples with slots at 0^0 to 40^0. This shows the effect of angular slots towards the eddy current distributions. Figure 3 shows the visualisation (3D and top view) of a magnetic field distribution of an unflawed sample as measured along the z-axis of the coil. As we can see, the magnetic field coming from the coil shows a distribution which corresponds to the shape of the coil itself. Region near the coil shows a high magnitude of field and drops abruptly with distance from the coil. This shows that the magnetic field intensity is a function of the position inside the coil radius.

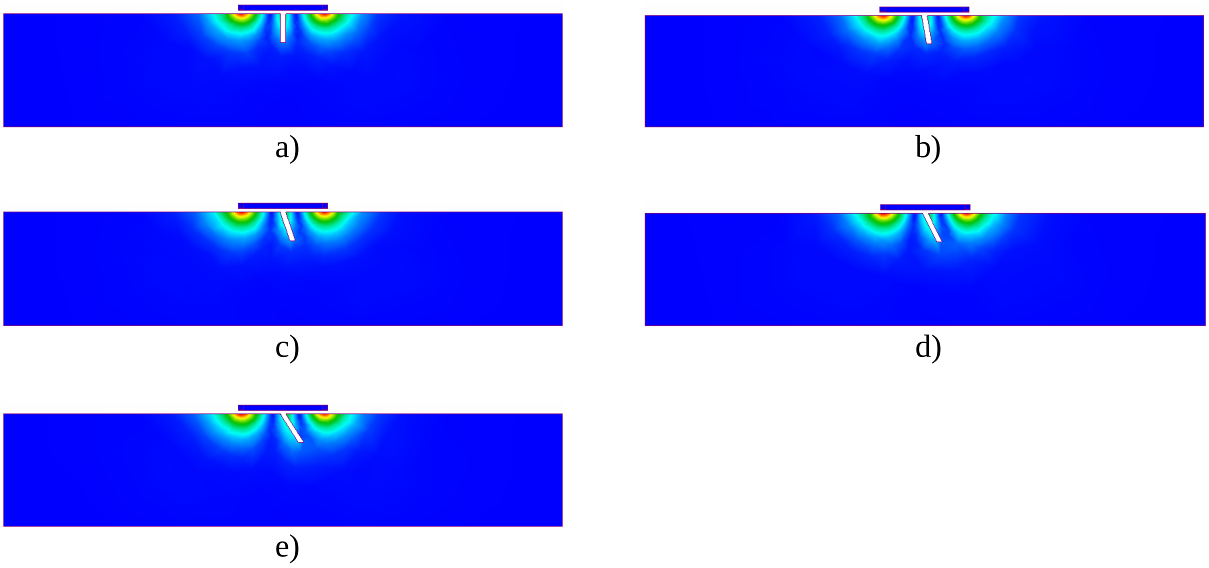
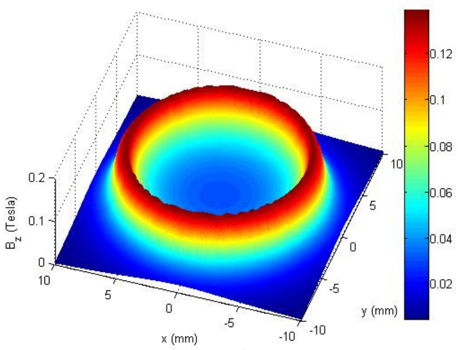


Figure 2. Simulated eddy current distribution for different angular slots (a) 0^0, (b) 10^0, (c) 20^0, (d) 30^0 and (e) 40^0

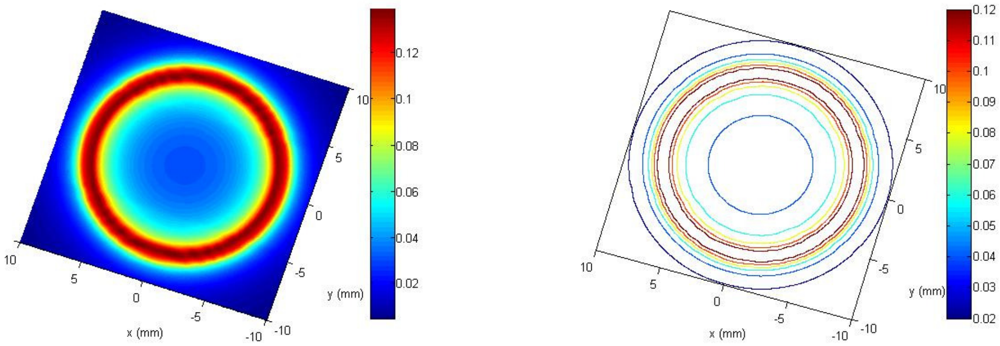
The magnitude of change in the magnetic field distribution from an unflawed and flawed sample is relatively small. To visualise the change of the magnetic field due to the angular slots, the visualisation was made by taking the difference between the magnetic field distribution of flawed sample and that of unflawed sample. In the visualisation construction of the differential magnetic field, data acquisitions were performed at two different models; one for sample with flaw and the other is for the unflawed. The differential magnetic field visualisations for all the angular slots can be mathematically defined as follows:

$$\Delta B_{Zm} = B_{Zm} - B_{Zref} \tag{1}$$

where B_{Zm} is the magnetic field for sample with flaw, B_{Zref} is the magnetic field for unflawed sample and m represents the slots with angle $m = 0^0, 10^0, 20^0, \ldots\ldots, N^0$.



a)



b) c)

Figure 3. Magnetic field visualisation from an unflawed sample measured along the z-axis of the coil; (a) 3D visualisation and (b) top view visualisation by color map (left) and contour map (right)

4. Angular Slots Characterisation

The magnetic field distribution from angular slot was simulated and the 3D visualisation of the field was implemented and analysed for the slot characterisation. In this part of the simulation, data acquisitions were made at temporal responses from the early stage of the transient magnetic field until it reaches its steady state. The objective here is to visualise the magnetic field distribution change at temporal responses for slot characterisation as the induced eddy current penetrates into the sample. Figure 4 shows an example of a transient signal measured at the centre of a coil.

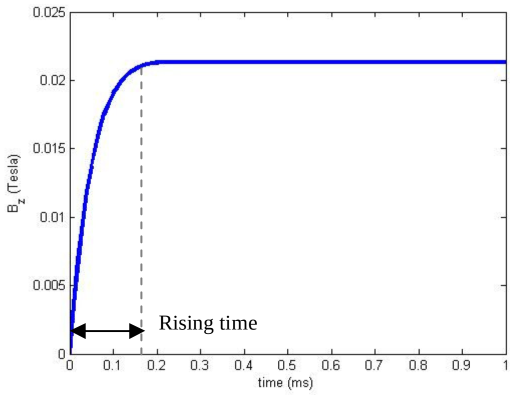
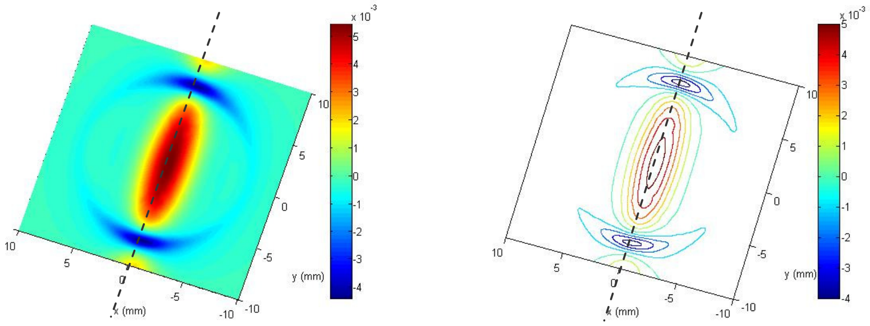
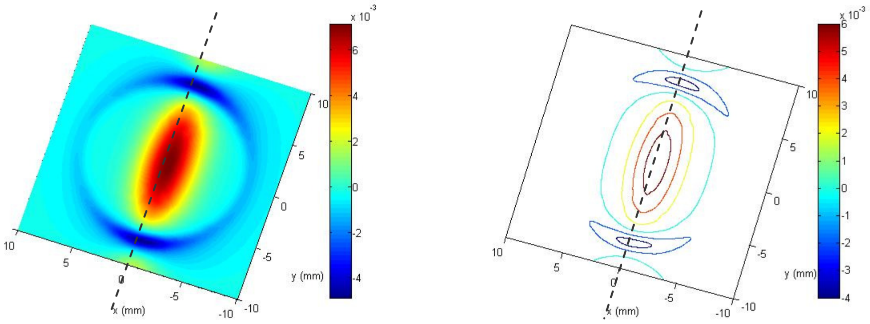


Figure 4. Example of a transient signal

Figure 5a to Figure 5d shows the visualisation (top view) of the differential magnetic field from the 30^0 angular slot at 0.04 ms, 0.08 ms, 0.12 ms, 0.16 ms and 2.00 ms respectively. The magnetic field mapping shown in the figures shows how the magnetic field distribute with time. In the early stage of the temporal transient magnetic field response, at 0.04 ms, we can see that the peak of the distribution is more localised at the centre of the coil which correspond to the opening of the slot. As the time increases, we can see that the peak distribution begins to shift and the area of the differential peak magnetic field distribution is at its maximum at the steady state of the transient as an effect to the interaction between the eddy current and the 30^0 angular slot. These shows that, by analysing the magnetic field temporal transient responses feature we can make the characterisation of an angular slot as the eddy current penetrates into the sample. It has indicated that the temporal transient magnetic field analysis have better discrimination information for defect sizing and characterisation than static responses. With the advantages of PEC sensor arrays over a single sensor, the temporal responses from the transient magnetic field can provide more structural information for defect detection and quantification [13].



a)



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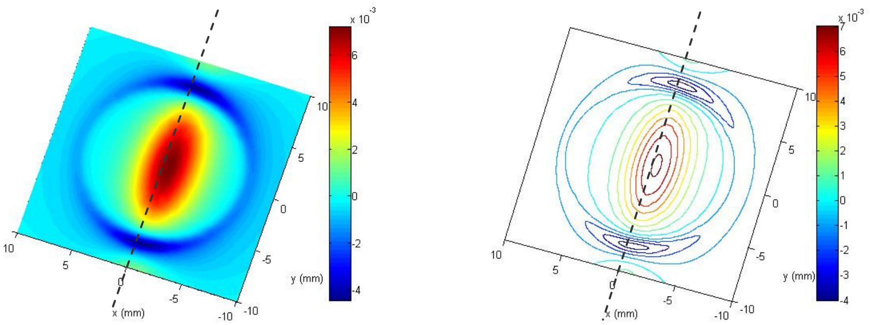

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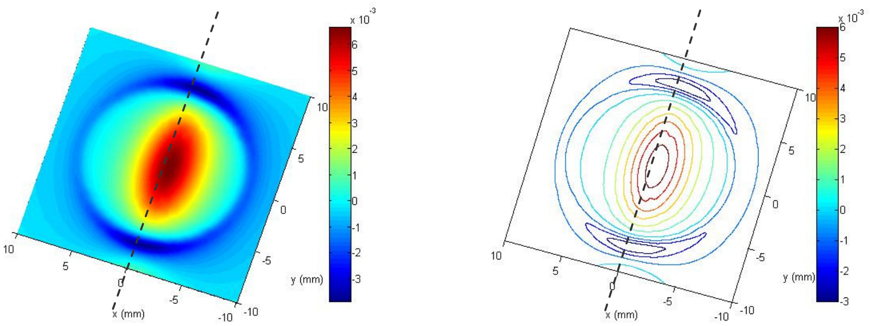

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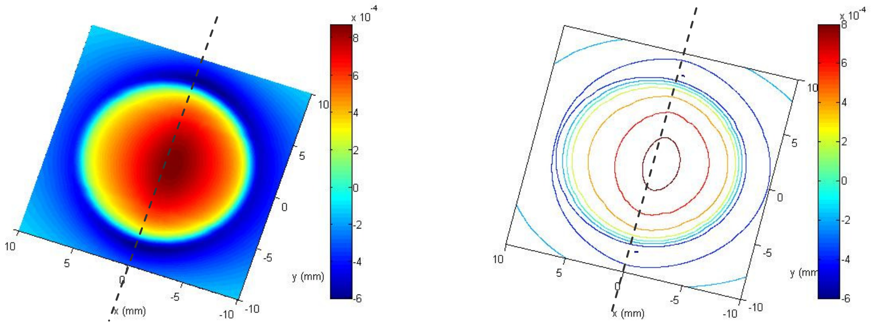
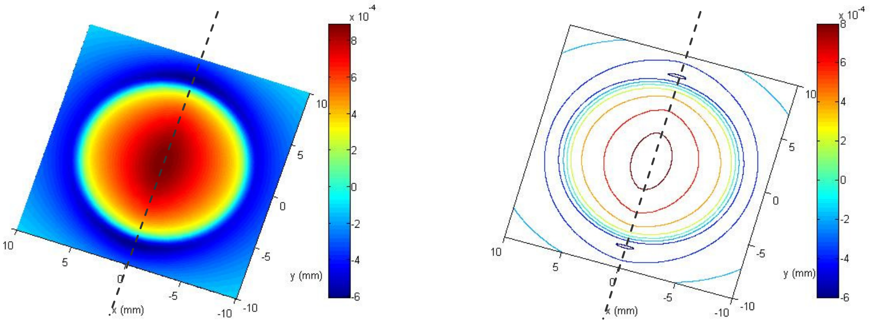


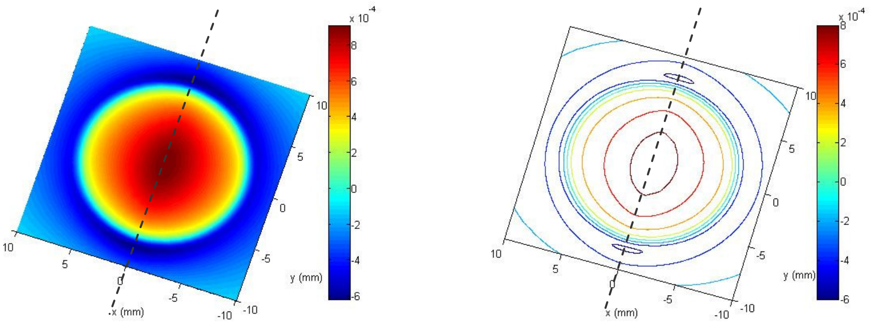
e)

Figure 5. Simulated differential magnetic field visualisation of 30^0 angular slot at (a) 0.04 ms, (b) 0.08 ms, (c) 0.12 ms, (d) 0.16 ms and (e) 0.20 ms

Magnetic field distributions from slots with different angle were then simulated and the 3D visualisations of the fields was mapped and analysed for angle discrimination between the slots. Simulations of angular defects were made with defect angles of 0^0, 10^0, 20^0, 30^0 and 40^0. Data acquisitions were made at 1 ms for every slot. The objective here is to visualise the magnetic field distribution profile change with defect angle for angular slots identification. Figure 6a to Figure 6e shows the visualisation (top view) of the differential magnetic field with angular slots from 0^0 to 40^0 respectively.



a)



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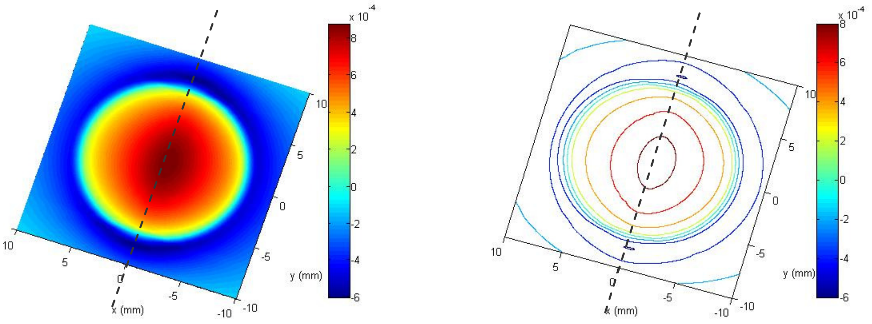

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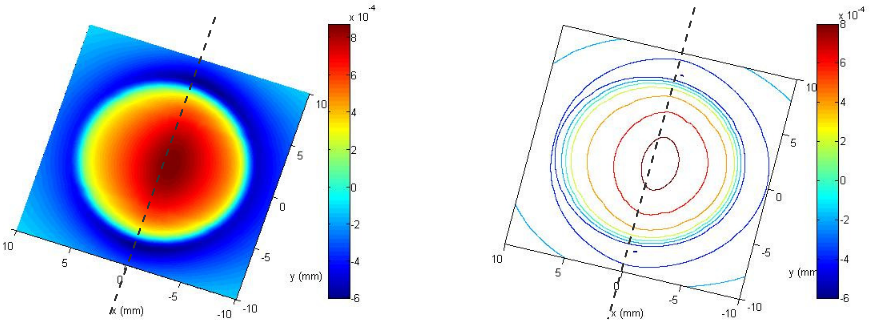

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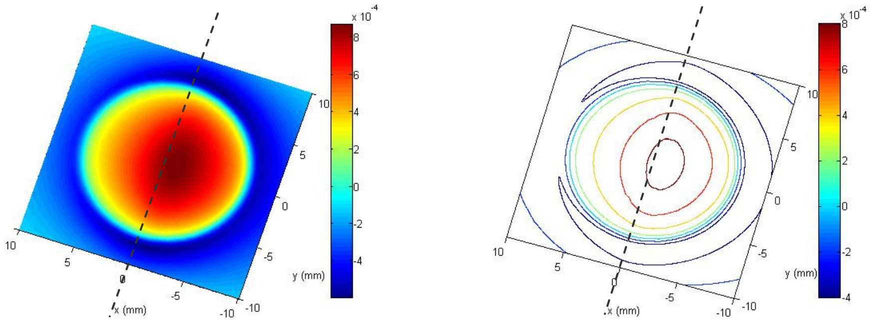

e)

Figure 6. Simulated differential magnetic field visualisation for (a) 0^0 angular slot, (b) 10^0 angular slot, (c) 20^0 angular slot, (d) 30^0 angular slot and (e) 40^0 angular slot

As we can see from the maps shown in the figures, it shows that as the angle of the slots varies from 0^0 to 40^0, the peak of the distribution is shifted towards the right which correspond to the slots angle direction inside the sample. Analysing the visualisation results obtained, it was found that the peak magnetic field distribution of the angular slots will be shifted corresponding to the angle of the slots as it increases from 0^0 to 40^0. From here, we can make the angle identification of the slots based on how the magnetic field is distributed from the interaction of eddy current and the angular slots in the sample.

5. Conclusion and Future Work

Visualisation of transient magnetic field mapping for complex geometry defects is of great importance for the design of inverse model for defect identification including features application of magnetic field distribution for defect discrimination and quantification. It also gives benefits for the development of sensor array(s) for defect characterisation. Based on the simulations carried out in this work, we have explored the means of complex geometry defect characterisation via the visualisation of the transient magnetic field mapping. A feature from the transient magnetic field visualisation has been used for characterisation of an angular slot based on how the magnetic field from the slot distributes with time. The temporal analysis of the transient responses for angle identification provides more information than static responses since the discriminations can be obtained and analysed as the induced eddy current penetrates into the sample. The changes of magnetic field distribution profile for different angular slots have also been mapped and analysed for angle identification from the interaction of eddy current and the angular slots in the sample.

Future work will be focused on (1) how to design a sensor array for the visualisation of the magnetic field mapping and optimising the design of array layout and performance, i.e. spatial resolution based on the magnetic field distribution and magnetic sensitivity. (2) To investigate the computational time and accuracy of FEA in contrast to analytical modelling and analysis in an attempt to built up a fast an accurate model that facilitates the inverse process for quantitative evaluation of specimens from the acquired magnetic field mapping. (3) Feature extraction from magnetic field distribution for defect characterisation and quantification. (4) More realistic type of defects and measurement conditions i.e. subsurface defects, lift-off problems with complex geometry samples and etc, will be simulated to visualise the resulting magnetic field distribution to broaden the application of the 3D visualisation features and its advantages.

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